Effects of Long-Term Recycled Wastewater Irrigation on Visual Quality and Ion Concentrations of Ponderosa Pine[1]

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Abstract

Recycled wastewater (RWW) has become a common water source for irrigating golf courses and urban landscapes. Ponderosa pine (*Pinus ponderosa*) is commonly used in urban landscape settings in the Rocky Mountain West. To evaluate the effects of RWW irrigation on quality and needle ion accumulations of ponderosa pine, eight landscape facilities near metropolitan Denver, CO, were selected for the experiment. Among these sites, four had been irrigated exclusively with domestic RWW [electrical conductivity (EC) = 0.84 dS/m] for 5, 6, 15, and 20 years, respectively. The other four with similar turf species, age ranges, and soil textures had been irrigated with surface water (EC = 0.23 dS/m). Ponderosa pines grown on sites irrigated with RWW exhibited 10 times higher needle burn symptoms than those grown on sites irrigated with surface water (33% vs. 3%). Tissue analysis indicated that ponderosa pine needles collected from sites receiving RWW exhibited 11 times greater Na^+ concentration, 2 times greater Cl^-, and 50% greater B concentrations than samples collected from the control sites. Stepwise regression analysis revealed that the level of needle burn was largely influenced by leaf tissue Na^+ concentration. Tissue Ca level and K/Na ratio were negatively associated with needle burn symptoms, suggesting that calcium amendment and K addition may help mitigate the needle burn syndrome in ponderosa pine caused by high Na^+ in the tissue.

Index words: salinity, sodium, turf.

Species used: Ponderosa pine (*Pinus ponderosa* L.).

Significance to the Nursery Industry

Growing concerns of our future water supply and more stringent wastewater discharge standards to surface water bodies have contributed to increasing interest in using recycled wastewater for urban landscape irrigation. Increasing numbers of landscape facilities and development areas have been switched to or plan to use recycled wastewater for irrigation in the western states. Landscape managers have observed chronic quality decline of some landscape plants under such practice. Information regarding the cause of the decline and the relative tolerance of different landscape plants to recycled wastewater irrigation is urgently needed in the landscape industry. This information will help landscape managers to make informed decisions. Proper selections of landscape plant and development of best management practices are critical to the long-term success of water reuse in urban landscapes and the landscape industry.

Introduction

The rapid population growth in many municipalities of the arid and semi-arid western United States has increased demands on limited fresh water supplies. Many cities and water districts are struggling to balance water use among municipal, industrial, agricultural, and recreational users. The population increase has not only increased the fresh water demand but also increased the volume of wastewater generated (16). Treated or recycled wastewater appears to be the only water resource that is increasing as other sources are dwindling. In addition to growing concerns of our future water supply, the more stringent wastewater discharge standards to surface water bodies have also contributed to increasing interest in using recycled wastewater for urban landscape irrigation. An increased number of landscape facilities have switched to or plan to use recycled wastewater for irrigation in the western states.

One of the issues that comes with using recycled wastewater for irrigation is landscape plant performance. Quality decline of some conifer trees (especially ponderosa pine) has been observed on golf courses and parks in Colorado with recycled wastewater for irrigation. The degree of the decline of some conifer trees appeared to relate to water quality, species, soil texture, irrigation methods, and drainage effectiveness (8). There is limited information available concerning effects of irrigation with RWW on landscape plants' quality and salt accumulation in the plant tissues. Landscape managers suggested that the quality decline of pine trees might be linked to salinity effect and/or a specific ion effect, and/or landscape management practices.

Although ponderosa pine is native and widely planted in Colorado, the most abundant growth takes place on deep, moist, and well-drained soils (3). Information about the sensitivity of ponderosa pine to RWW irrigation is not currently available in the literature.

In this study, we examined both the degree of decline symptom of ponderosa pines grown on golf courses and a city park that have been irrigated with RWW for 5–20 years, in comparison with ponderosa pines grown in landscapes with similar age ranges, soil texture, landscape management practices, and plant species, but using surface water for irrigation; and assessed individual ion accumulations in pine

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Table 1. Age, years of recycled wastewater irrigation (RWI), principle soil series, and surface texture of principle soil series of golf courses and city parks selected for the project to evaluate long-term recycled wastewater irrigation on soil properties and landscape plant health.

Experimental site	Age	Years of RWI	Water source	Principle soil series	Surface texture classification
Golf Course I	8	6	RWW	Renohill Ulm Platner	Clay loam Clay loam Loam
Golf Course II	48	20	RWW	Renohill Nunn Bresser	Clay loam Clay loam Sandy loam
Golf Course III	14	14	RWW	Nunn Arvada	Clay loam Loam
City Park I	6	5	RWW	Platner Ulm	Clay loam Silt clay
Golf Course A	34		Ditch	Loveland	Clay loam
Golf Course B	39		Ditch	Nunn	Clay loam
Golf Course C	14		Ditch	Table Mountain Paoli Caruso	Loam Loam Loam
City Park A	8		Ditch	Nunn Fort Collins	Clay loam Loam

needles and the relationship of the degree of ion accumulation with visual decline symptoms.

Materials and Methods

Study sites and irrigation water sources. Six golf courses and two city parks near metropolitan Denver, CO, area were selected for the study (Table 1). Ponderosa pine trees were typically grown on the irrigated roughs along fairways of golf courses and along walkways and driveways in city parks. Turfgrass grown understory on all landscape sites were Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.), or a mixture of both. Turfgrasses were mowed at 5.1–7.6 cm (2.0–3.0 in) during the growing season. Among these sites, golf courses I, II, and III had been irrigated with RWW for 6, 14, and 20 years, respectively. City Park I had been irrigated with RWW for 5 years by 2004 (Table 1). On the recycled wastewater irrigation sites, RWW is generated and transported from three advanced wastewater treatment plants, stored in irrigation ponds, and used exclusively as the only irrigation water source. Reuse sites received approximately 65 cm (26 in) of RWW to irrigate turf and trees and were fertilized with 75 kg/ha N annually.

Three golf courses and one city park with similar ranges in age, soil texture, landscape management regimes, and plant species, but irrigated with surface water were selected as controls (Table 1). Control sites were fertilized with 150 kg/ha N annually and received approximately 55 cm (22 in) of irrigation water annually.

Plant sampling from RWW-irrigated vs. surface water-irrigated sites. In 2004, ponderosa pine tree health on the eight landscape sites was evaluated. On each golf course site, 3 fairways were randomly selected. On each fairway, we drove from tee to putting green, the first three ponderosa trees that we encountered were visually rated for plant health and 2 branchlets were collected for plant tissue analysis. On the park site, three ponderosa pine trees were randomly selected and visually rated for plant health and 2 branchlets were collected from each tree for plant tissue analysis. The sampling height was 1.5–2.5 m (5.0–8.3 ft). The visual evaluation was done by rating the percent needle area that showed leaf necrosis (needle burn).

The sampled ponderosa pine branchlets were brought to lab and needles were separated to different age groups. One- and 3-year-old needles were selected for ion analysis. To measure ion concentrations, needles were rinsed with deionized water to remove possible contaminations from the surfaces and dried at 70C (158F) for 24 hr. Dried needles were ground in a Wiley mill to pass through a screen with 425-µm openings. Approximately 1 g of screened and dried sample were weighed and ashed for 7 hr at 500C (932F). Ash was dissolved in 10 ml of 1N HCl and diluted with deionized water. Solution aliquots were analyzed for Na^+ K^+ Ca^{++}, Mg^{++}, B, and other metals by inductively-coupled plasma atomic emission spectrophotometry (ICP-AES) (Model 975 plasma Atomcomp, Thermo Jarrell Ash Corp., Franklin, MA). Chloride was determined with a Cl-selective electrode (Model 96-17B, Thermo Electron Corp., San Jose, CA).

Data analysis. Data were subjected to analysis of variance (10) to test the effect of irrigation water source on the degree of needle burn symptoms and ion concentrations of pine needles. Stepwise regression and correlation analyses were performed to relate the degree of needle burn symptoms to plant tissue test variables (Table 3). Means were separated using Fisher's protected LSD.

Results and Discussion

Recycled wastewater sampled onsite exhibited an average EC value of 0.84 dS/m (Table 2). The chemical constituents of recycled wastewater were dominated by sulfate, bicarbonate, chloride, and sodium. Adjusted sodium absorp-

Table 2. Average water quality values of ditch water and recycled wastewater (RWW) from advanced wastewater treatment plants in Colorado.

	Average[z]	
Parameter	**Recycled wastewater**	**Ditch water**
pH	8.1 (0.6)	7.9 (0.3)
NH_4-N (ppm)	0.76 (0.20)	N/A
NO_3-N (ppm)	3.62 (0.33)	0.42 (0.16)
Total P (ppm)	0.47 (0.06)	0.10 (0.04)
Total dissolved salts (ppm)	614 (44)	126 (35)
Conductivity (dS/m)	0.84 (0.07)	0.23 (0.08)
SAR	3.1 (0.2)	0.9 (0.2)
Adjusted SAR	5.0 (0.3)	1.2 (0.2)
Sodium (ppm)	99 (5)	15 (5)
Chloride (ppm)	95 (6)	8 (4)
Bicarbonate (ppm)	112 (7)	57 (21)
Calcium (ppm)	61 (3)	16 (6)
Magnesium (ppm)	15 (1)	5 (2)
Sulfate (ppm)	160 (10)	25 (19)
Boron (ppm)	0.23 (0.02)	0.04 (0.01)
Iron (ppm)	0.35 (0.07)	0.53 (0.30)
Potassium (ppm)	12.7 (2.2)	0.90 (0.05)

[z] Average values of 37 RWW samples and 5 ditch water samples, respectively. N/A = not available. Numbers in parenthesis indicate standard error.

tion ratio (SAR), calculated using the adjustment procedure documented by Westcot and Ayers (18), of recycled wastewater from reuse sites ranged from 1.6 to 8.3. The average sodium and chloride concentrations of 37 water samples collected from all the sites were 99 mg/liter and 95 mg/liter, respectively. Most of the surface water used on the control sites came from melting snow of the Rocky Mountains and had average EC, SAR, sodium and chloride concentrations of 0.23 dS/m, 0.9, 15 mg/liter, and 8 mg/liter, respectively (Table 2). The RWW had about 11.9-fold higher Cl^-, 6-fold higher Na^+ and SO_4^-, and 3-fold greater Ca^{++}, Mg^{++}, and EC than surface water (Table 2).

Greater variations (CV = 37.4) in the incidence of needle burn or dieback existed among plants of ponderosa pine under RWW irrigation. On average, ponderosa pines grown on sites irrigated with RWW exhibited 10 times greater needle burn symptoms than those grown on sites irrigated with surface water (33 vs. 3%) (Table 3). The needle burn symptoms included needle tip necrosis, resin-infiltrated bands, and necrosis of distal regions of the needles. Severely affected trees exhibited needle dropping and/or thinning. We observed a few of the trees had died and those trees were excluded from the quality evaluation and sample collections.

The ion concentrations in the needles were not different between year 1 and 3 needles; therefore, data were pooled for analysis. Tissue analysis indicated that ponderosa pine needles collected from sites irrigated with RWW exhibited 11 times greater Na^+, 2 times greater Cl^-, and 50% greater B concentrations than samples collected from the control sites (Table 3). The needle K/Na ratio of ponderosa pines receiving surface water for irrigation was 12.4, compared to 1.0 in RWW irrigated pines. In addition, ponderosa pine receiving RWW for irrigation had 39, 20, 148, 84, 31, and 53% higher Mn, P, S, Si, Ba, and Li concentrations in needles when compared to surface water irrigated ponderosa pines. Despite the fact that Mg concentration was 2-fold higher in RWW than surface water (Table 2), needle Mg concentration was 19% lower in RWW-irrigated pine than those receiving surface water (Table 3). This may reflect the replacement of Mg^{++} with Na^+ in soil cation exchange sites. Therefore, the chemical concentration in foliar tissue perhaps was not only influenced by the chemical constituents of RWW, but also by the

Table 3. Mean needle ion concentrations of ponderosa pine grown on sites under long-term recycled wastewater (RWW) irrigation vs. surface water irrigation.[z]

Parameters	Surface water	Recycled waste water
Soil EC (dS/m)	0.89	1.85**[y]
Needle burn (0–100%)	3.17	33.58****
Al [z]	131.11	125.76
B	32.69	50.27***
Ca	3827.10	3321.00
Fe	167.79	149.52
K	2421.80	2497.80
Mg	1273.80	1030.90*
Mn	26.77	37.13**
Na	195.60	2475.20****
Cl	1383.00	3248.00**
P	869.41	1042.83*
S	391.20	971.50****
Si	393.01	722.38****
Zn	21.59	24.93
Ba	2.12	2.77**
Cd	0.06	0.06
Cu	2.56	2.74
Li	6.39	9.80***
Mo	0.32	0.33
Ni	0.17	0.15
Sb	0.09	0.05
Sr	16.47	14.88

[z] unless indicated, unit is mg/kg.

[y]*, **, *** Significantly different from surface water-irrigated sites at *P* = 0.05, = 0.005, and < 0.001, respectively.

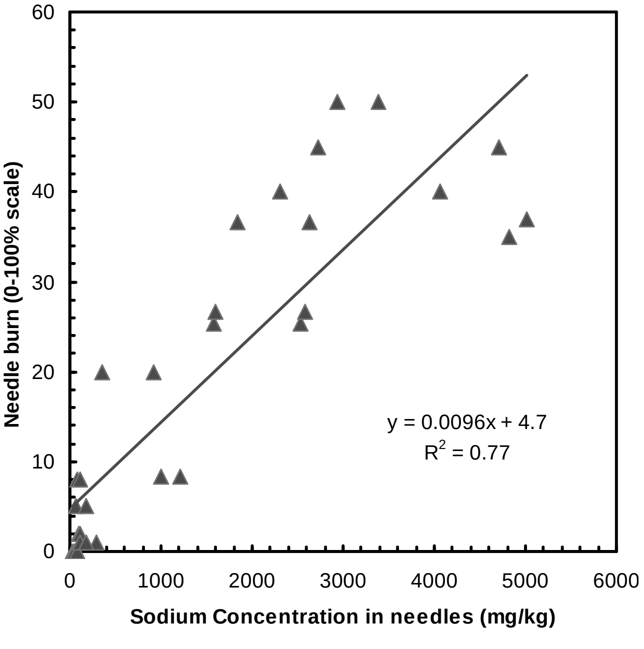

Fig. 1. Linear regression of the degree of needle burn and sodium concentration in needles of ponderosa pine subjected to recycled wastewater for irrigation.

Table 4. Regression equations obtained using stepwise analyses for the degree of needle burn [Ponderosa needle burn ($R^2 = 0.99$, n = 32)].

Variable	Parameter	Standard error	Sum square	F value	P value
Intercept	–8.75	3.77	37.9	5.4	0.03
Na	0.0058	0.00063	592	84.4	0.0001
Cu	9.79	1.66	245	34.9	0.0001
Ni	26.2	9.7	50.9	7.3	0.02
Ca	–0.0023	0.00057	111.7	15.9	0.002
K/Na	–0.35	0.039	585	83.4	0.0001

individual salts' readiness to leach, uptake and transport by plants, ability to compete with other ions, and compartmentation characteristics.

The needle burn symptom (including needle tip necrosis, a reddish brown color and a distinct boundary between the healthy and damaged parts of the needle) and high tissue Na and Cl accumulations have been described as typical symptoms of salt injury (13). Previously, Staley et al. (12) also described the foliar chlorosis and tipburn syndrome of ponderosa pine in the Denver area. After more than 10 years of examination and cultural treatment that implicated no fungal or insect causal agents, they found that the affected needles contained abnormally high levels of Na^+. The levels were 13 times higher than needles of healthy trees. The authors did not specify the source of Na^+. In a greenhouse study, Spotts et al. (11) found that ponderosa pine tipburn syndrome was first observed on chloride salt-treated ramets. They also found that pine injury that resulted from NaCl exceeded the injury degree induced by Ca and Mg chlorides.

Relationship of visual quality decline and degree of ion accumulations. Regression analysis revealed that needle burn was largely influenced by needle Na^+ concentration with a linear regression coefficient of 0.77 (Fig. 1 and Table 4), indicating increasing needle burn was at least partially associated with the Na^+ accumulation in the needles. When needle Na^+ concentration increased beyond 1500 mg/kg, leaf tip burn became visually apparent. In a study evaluating the impact of NaCl applied to highways for deicing on pines and cedars, Hofstra and Hall (6) also found that the percentage of necrotic foliage and the percentage of Na^+ and Cl^- in the leaf tissue were closely related.

In addition to Na concentration, stepwise regression analysis revealed that increasing Cu and Ni also exhibited positive relations with increasing levels of needle burn (Table 4), although needle Cu and Ni concentrations did not differ significantly between surface water- and RWW-irrigated ponderosa pines (Table 3). Tissue Ca^{++} level and K/Na ratio were negatively associated with needle burn, suggesting Ca^{++} amendment and K^+ addition may help mitigate the needle burn syndrome in ponderosa pine associated with high Na^+ in the tissue (Table 4). In a greenhouse study, Warren et al. (17) found that $CaCl_2$ amendment improved shoot growth and visual appearance of loblolly pine (*Pinus taeda* L.) irrigated with untreated laundry wastewater. Supplemental additions of Ca^{++} have been found to improve soil structure, water infiltration, and leaching. The actions of Ca^{++} in salt stressed plants also include the reduction of sodium binding to cell walls and plasma membrane, alleviating membrane leakiness, and preventing salt-induced decline in cell production and elongation (1, 9), and improving uptake of important nutrients such as K^+ (2). Metabolic toxicity of Na^+ is also a result of its ability to compete with K^+ for binding sites essential for cellular function. More than 50 enzymes are activated by K^+, but Na^+ cannot substitute in this role (14). Thus high levels of Na^+ or low K/Na ratio can disrupt various enzyme processes in the cytoplasm. The decline in ponderosa pine health in this study might be associated with failure of maintenance of adequate K/Na ratio.

Different conifers and pine species differ in their salt tolerance. In a greenhouse study to assess salinity tolerance of 20 landscape trees and shrubs, Monk and Peterson (7) ranked ponderosa pine as intermediate in its salinity tolerance. During the 2-year experiment, ponderosa pine survived irrigation water at 6,000 mg/liter total dissolved salts, whereas nine other species [including blue spruce (*Picea pungens* Engelm.), Douglas fir (*Pseudotsuga menziesii* Franco), black walnut (*Juglans nigra* L.), and linden (*Tilia cordata* P. Mill.)] did not survive the lowest salt treatment (4,000 mg/liter total dissolved salts). In comparison, five species [including black locust (*Robinia pseudoacacia* L.) and honeylocust (*Gleditsia triacanthos* L.)] survived 10,000 mg/liter salt treatment. In evaluating various pine species in Southern Ontario that were grown along the road side and subjected to winter NaCl deicing, Hofstra and Hall (5) reported that white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* L.) were highly damaged, Scots pine (*Pinus sylvestris* L.) was moderately damaged, and Austrian pine (*Pinus nigra* Arnold.) and mugo pine (*Pinus mugo* Turra) suffered little damage. The authors further demonstrated that although Austrian and mugo pine generally were far less damaged than other pines, individual plants showed varying amounts of injury. However, all pines contained similar levels of Na^+ and Cl^- at similar levels of damage. Townsend and Kwolek (15) found that ponderosa pine have a higher salt tolerance than white pine and cembra pine (*Pinus cenbra* L.), and Scots pines. From studies conducted in northern California and Nevada using synthetic wastewater, Jordan et al. (7) and Wu et al. (19) found that some pines, including Stone pine (*Pinus pinea* L.), Mondell pine [*Pinus eldarica* (Medw.) Silba.], and Aleppo pine (*Pinus halepensis* L.), were salt tolerant and were recommended for use in sites with RWW sprinkler irrigation.

Both problems and opportunities exist in using RWW for landscape irrigation. The use of recycled wastewater for irrigation in urban landscapes is a powerful means of water conservation and nutrient recycling, thereby reducing the demands of freshwater and mitigating pollution of surface and ground water. However, potential problems associated with recycled wastewater irrigation exist. Salts (especially the relatively high Na^+ and high EC) in the treated wastewater were associated with needle burn symptoms observed in ponderosa pines subjected to RWW irrigation. Other factors may have also contributed to the severity of the injury symptoms. For example, the drier than usual climate during 2002–2003 growing season might have increased the severity of pine injury. Low levels of precipitation reduce leaching of excess

Na$^+$ and Cl$^-$ from needles and thus enhanced injury. Our data indicate needle tipburn was largely associated with needle sodium concentration. However, it is unclear if Na$^+$ is absorbed by leave surface wetted by sprinkler irrigation or by salts accumulated in the soil or by combination of these two. In our previous studies, we found soils from sites with RWW for irrigation exhibited 200% (278 mg/kg) higher concentration of extractable Na$^+$ and 24% higher concentration of extractable Ca than sites irrigated with surface water (8).

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